Semi Rigid and Adjustable CFRP Membrane for Radio Telescope Applications

D. Giles and S. Kulick
Composite Optics, Inc.
9617 Distribution Ave. San Diego, CA 92121
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Abstract:

High accuracy, very light-weight carbon fiber reinforced plastic (CFRP) membrane reflectors have been demonstrated by Composite Optics, Inc. (COI) for applications in ground-based, millimeter wave radio astronomy. The figure of a semi-rigid membrane can be significantly improved by suitably altering the adjustment of an array of passive adjusters that support the membrane. A factor of ten contour improvement is possible. First, the surface is measured and analyzed for Zernike error modes. Then an adjustment scenario, dictated by a customized software program, is applied to the adjusters. This process is repeated to produce dimensionally stable reflectors several meters in diameter at or below 0.001 inch rms.

Keywords: *adjustable reflector, CFRP, millimeter wave radio astronomy*

Millimeter wave radio astronomy is of great interest to the scientific community and particularly to the National Radio Astronomy Observatory (NRAO). NRAO currently has plans to produce a radio telescope to operate between the frequencies of 30 and 900 Ghz. The radio telescope, known as the Millimeter Array (MMA), will consist of an array of 36 ten meter diameter parabolic reflector surfaces and will be located at Llano de Chajnantor, a plateau at 16,400 feet elevation, in Chile. This shorter wavelength instrument places a significant burden on the surface accuracy and thermal performance of the antenna.

Attempts have been made to construct the antenna reflective surfaces from carbon fiber composite panels in a sandwich construction using aluminum honeycomb as the core. In one notable example in France, each panel, in the order of a meter square, was supported at each of four corners and adjusted in tip, tilt and focus to form an accurate (25µm rms) reflecting surface. The panels themselves were relatively rigid structures. Unfortunately, this approach, although lightweight, reasonably stable over temperatures and sufficiently accurate, was not without problems. The reflective surface was a very thin layer of vapor-deposited aluminum (VDA) on the composite surface. The installation, based on technology several years old, had suffered from some erosion and corrosion problems. In spite of the presence of a protective coating, the surface was punctured in several locations. Each of these openings became a corrosion site. There have also been reports of delamination between the carbon fiber-reinforced plastic (CFRP) composite faceskins and the aluminum core. With this as anecdotal background, it is not surprising that there are questions about future use of a CFRP as an integral part of the reflecting surface. These concerns do have merit. It is also true that there have been recent advances on several fronts that justify examining the use of CFRP for the reflector membrane.

Composite Optics, Inc. (COI) has developed a novel and low-cost method for fabricating large, high-accuracy reflector surfaces. Dubbed the adjustable membrane approach, this method entails fabricating a thin and uniform membrane surface and later adjusting the contour with an array of adjusters to within acceptable limits. Since the panels are adjusted as a final operation, the inherent difficulties and expenses associated with fabricating metal-coated rigid panels are eliminated. Analytical results and empirical data both substantiate achievable contour improvements of an order of magnitude or more. Thus an adjustable panel for the MMA radio telescope may be manufactured at 50 to 127µm rms and adjusted within tolerance to 12µm rms.

COI's adjustable membrane concept could replace the rigid panels and not suffer from the inherent durability issues connected with aluminum honeycomb core sandwich construction and thin metallic surface coatings. Finally, alternate metallization processes not possible with a rigid body panel will use a much thicker metal layer and will produce a more durable reflective surface.

Approach:

The feasibility of producing rigid, composite, sandwich panels for high accuracy reflector surfaces has been demonstrated by MAN Technologies of Munich[i], Germany and Mitsubishi Electric Corp. of Tokyo, Japan[ii] and by COI. The costs of manufacturing highly accurate reflector surfaces may be significantly reduced if this new approach is taken.

A solid CFRP laminate has significant in-plane stiffness but is able deflect under small transverse loads. Therefore, a reflector panel having a certain error as manufactured can be distorted by an array of passive adjusters to improve the surface figure. In this concept, a reflector surface is manufactured from conventional pre-impregnated (prepreg) carbon fiber reinforced epoxy material by a hand layup process and cured in an oven or autoclave. The reflector membrane is a uniform, isotropic layup of CFRP and does not use any honeycomb core material. Because the manufacturing error will be adjusted out at a later time, the issues of mold thermal expansion and thermal lag during cure are of small significance as are the effects of internal stresses caused by temperature gradients upon heat up and cool down. A thin layer of aluminum foil, between 0.002 and 0.005 inch thick, is applied to the CFRP membrane on both the front and back surface and the part is molded in such a way that the metal surface exactly matches the figure of the layup mold. The foil creates an electrically conductive layer for microwave reflectivity which is significantly thicker and more durable than the VDA or aluminized plastic film coating typically used in a rigid panel concept. The foil method works in this capacity because the membrane surface will be adjusted after the manufacturing process; otherwise, the effect of dissimilar thermal expansion between the metal and composite would yield unacceptable contour results in a rigid panel concept.

To verify that a reflector surface may be adjusted from the as-manufactured figure to the requirement of 12 µm rms, an analytical model was developed using MSC Nastran finite element modeling (FEM) software. A model of the parabolic reflector surface was created and a series of unit loads was applied to each of the possible adjuster node locations in the model. The axis symmetry of a center-fed paraboloid was employed to minimize the number of FEM load cases required, thus a single radial set of applied loads was extrapolated to characterize the influence of a unit load applied at any adjuster location for the entire surface of the membrane. The resultant influence coefficient matrix was used to calculate the required load application at each adjuster node; this minimizes the total surface rms error for a given set of adjuster coordinates and a database of measured (or assumed) surface figure errors. Countless model cases and analyses led to the following conclusions regarding the adjustability of a 3.3M reflector:

- At 0.12 inches thick, a large number of adjusters (> 258) will be needed to bring an initial 127 µm rms (assumed) into acceptable limits (< 12 µm).
- Thicker membranes are "better" from an adjustment standpoint.
- The 0.20 inch thickness shows potential for adjusting while utilizing a smaller amount of composite.
- Adjuster placement can be manipulated to specifically reduce certain modes.
- Specific rms targets can be used to define the minimum number of adjusters needed.

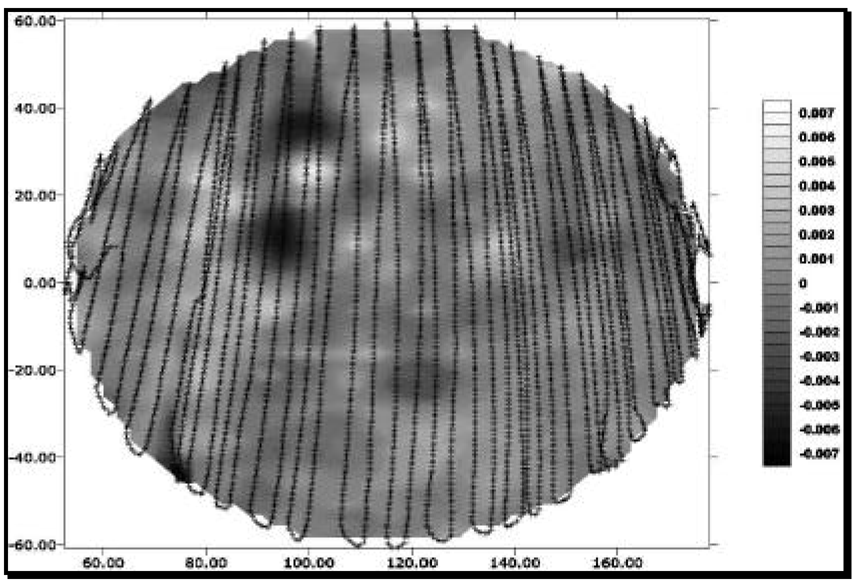
Dr. John Kibler of COI, has written an integrated, Windows based program to perform all of the calculations and analysis required to inspect, analyze, diagnose, and adjust a reflector surface. The software also includes many other engineering and analysis capabilities commonly used by COI reflector engineering. Since the adjustment analysis was added to an already existing program, its capabilities inherently address the unique requirements for building and analyzing Zernike shaped reflectors, as well as spheres, parabolas, hyperbolas, planes and cylinders.

Given that a reflector surface is required to be iteratively inspected and adjusted, and given the measurement precision required to verify a large reflector to 12 µm (0.0005 inch) rms, COI investigated an alternative method for inspecting the reflector surface. The baseline inspection device used at COI for large reflectors is a multi-headed theodolite system; however, a laser tracker device was brought in for evaluation and use in the fabrication of the test-bed adjustable reflector. A laser tracker is a single-headed device used to digitize a surface or component feature dimensions. It is similar to a single theodolite head in that it uses a pair of shaft encoders to measure elevation and azimuth angles. Unlike a theodolite, which uses two plus heads and triangulation to solve for a component dimension, a laser tracker uses a laser interferometer to measure distance. Thus with two angles and a distance measurement, a single head instrument can generate coordinates in three space. In operation, the laser beam is reflected back to the instrument by a spherically mounted retro-reflector (SMR). As the SMR is moved, the laser beam is steered by elevation and azimuth motors; the system tracks the SMR by maintaining the maximum reflected beam intensity. The SMR is dragged across a surface or feature while the tracker records the (x,y,z) coordinates at the center of the sphere over time.

COI used a Spatial Metrix Corp. (SMX) laser tracker, model 4500, which was also used for inspection and adjustment of the technology demonstrator reflector. A typical inspection map consisted of 6,000 to 8,000 points. Data points were collected with a .5 inch distance spacing in the x-direction and about a 2 to 4 inch spacing in the Y direction of the reflector. Figure 1 is a graphical representation of the surface error of the test bed reflector, including a '+' at each measurement point.

The laser tracker device performed exceptionally well, both in reducing the time required to perform an inspection and in improving the measurement accuracy capability over a theodolite system. Each surface inspection required one operator and took only 20 minutes from start to finish. This represents nearly a 60X improvement in data collection rate. The SMX laser tracker system and software offered some additional capability that was also taken advantage of during the inspection and adjustment operations performed on the breadboard reflector.

Figure 1. Inspection map and measured points.



Results:

Following the adjustment analysis and the development of an integrated inspection and adjustment software program, COI manufactured the test bed reflector to the following specifications:

Surface[1]:

- Shape: Parabolic surface of revolution
- Focal length = 132.5 inch

[1] The layup mold tool manufactured for the NASA ACTS– Advanced Communication Technology Satellite primary, 20GHz, transmit antenna was used for the fabrication of this demonstration reflector.

- Aperture = 3.3M Ø, offset
- Offset = 50 inch +Y direction

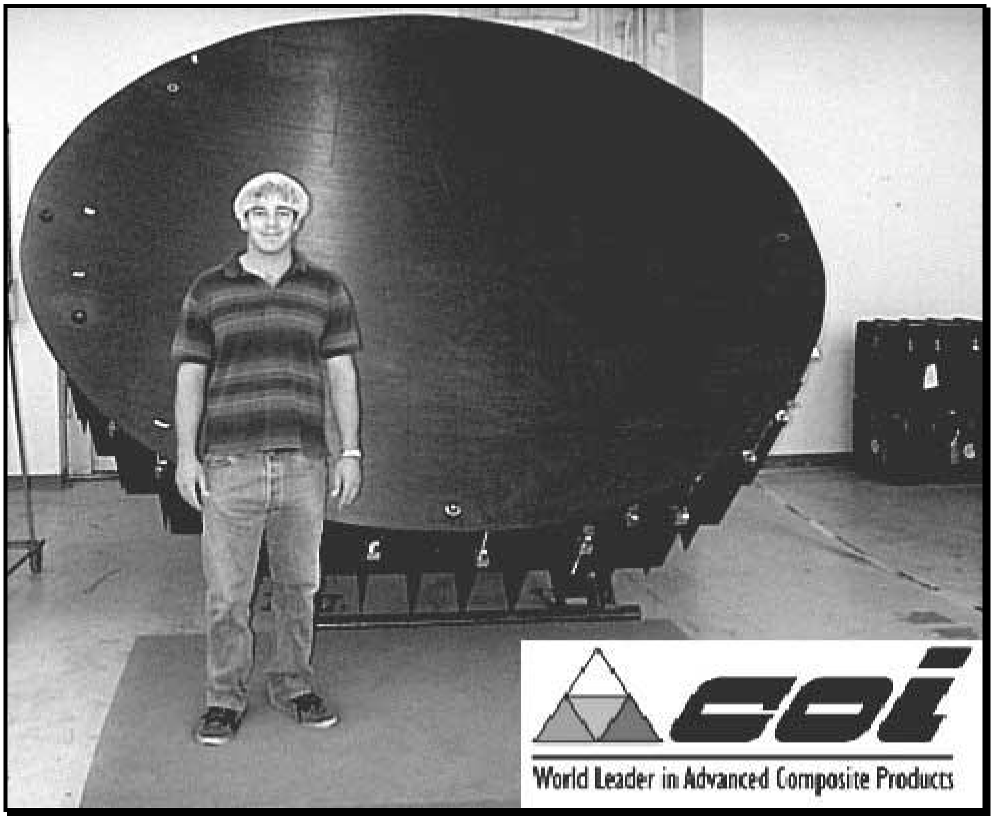
Laminate:

- Standard modulus (33 Msi) carbon fiber
- Unidirectional prepreg tape
- 0.200 inch thick, 16 plies, quasi-isotropic
- Between 57 and 107 adjusters

The reflector described above was manufactured at COI using low-cost CFRP materials and processing methods developed specifically for application in terrestrial, high precision reflector systems. After manufacture, it was supported on a rigid structure with passive micro-adjusters. The SMX laser tracker was used to inspect the surface and the integrated software program was used to assist with the adjustment analysis and prescription for the displacement and number of turns at each micro-adjuster.

While the mold tool had a 0.0043 inch rms with a 132.5 inch focal length, the first inspection of the reflector assembly (after trimming the edge of the laminate to size) revealed a 0.0078 inch rms. The increase in surface figure distortion is an inherent function of the mechanical and physical properties of the lower cost materials and processes selected for this application; to reiterate the direction is not to produce a rigid body reflector panel that comes off the mold immediately in tolerance. Beginning with only 57 adjusters on a 16 inch square grid (0.56 adjusters per square foot) the surface was adjusted to 0.0019 inch rms. Though the analysis predicted a 0.0016 inch rms was achievable given the quantity and position of the adjusters, more adjusters were added to gain better control of the reflector contour around the perimeter and to approach an improved surface figure. Ultimately, with 107 adjusters (1.05 adjuster per square foot) a surface figure of 0.0015 inch rms was achieved. A photograph of the breadboard reflector is shown in Figure 2 with the first author, 6’0” tall, standing in front of it.

Figure 2. Breadboard 3.3M Diameter Reflector.



Conclusion:

The concept of fabricating a semi-rigid and adjustable membrane reflector surface with low-cost materials and exceptional surface accuracy requirements was validated both empirically and analytically in this program. The parametric study of factors contributing to the overall surface adjustment concluded that, with a thicker membrane or more adjusters, the target accuracy for astronomical measurements at frequencies up to 900 Ghz could be met. The composites technology described in this paper is very well suited to applications in terrestrial radio astronomy with extreme tolerances for surface accuracy and dimensional stability and "down-to-earth" monetary budgets.

The adjustable membrane methodology for building large, high accuracy reflectors has been demonstrated to be technically feasible and to be a robust solution for terrestrial radio telescope applications. Because precision is applied once during the adjustment process and is not required to be maintained through the manufacturing process, the issue of applying a durable, thick, metallic coating for RF reflectivity is solved. Ultimately, the surface accuracy requirements for observations in the millimeter wavelengths can be achieved at relatively low costs compared to rigid composite panels and with greater dimensional stability than with machined metal panels.

Other possibilities for this technology are the creation of adjustable secondary reflectors for correction of wave front phase error caused by inaccurate primary reflectors, such as in a Cassegrain telescope. An adjustable reflector could be produced where the focal axis alignment can be adjusted by distorting the surface from the shape of one parabola into a new parabola with a different focal length, offset or focal axis pointing vector. A parabolic reflector could be adjusted to have many different Zernike aberration mode shapes.

References

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[ii] Tajima, T, et. al. CFRP Surface Panels for Radio Telescope. Mitsubishi Denki Giho Vol. 56 No. 7 p. 513-17 1982